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SELF-PRESERVING BUOYANT TURBULENT PLUMES

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Abstract. An experimental study of round buoyant turbulent plumes is described, emphasizing conditions where the flow has lost source momentum and other source disturbances, and has become self preserving. Plume conditions were simulated using dense gas sources in a still and unstratified air environment. Mean and fluctuating mixture fractions and velocities were measured using laser-induced fluorescence and laser velocimetry, respectively. The present measurements extended farther from the source than most earlier work (up to 151 source diameters and 43 Morton length scales) and show that self-preserving plumes are narrower and have larger mean properties near the axis than previously thought. Although contemporary turbulence models yield reasonably good predictions of mean properties in the self-preserving region, there are difficulties with many of the approximations concerning turbulence properties; this raises questions about the potential effectiveness of these models for predicting the properties of the complex buoyant turbulent flows that are encountered in practical fire environments.

Introduction. The structure of round buoyant turbulent plumes in still and unstratified environments is a classical problem that has been widely studied in order to gain a better understanding of buoyancy/turbulence interactions. Conditions far from the source are of particular interest, even though such conditions are rarely encountered in practice, because effects of source momentum and other source disturbances have been lost and the flow becomes self preserving. For such conditions, both theoretical considerations and the interpretation of measurements are simplified and flow properties provide a straightforward evaluation of turbulence modeling concepts. Motivated by these observations, the present investigation undertook new measurements of mean and fluctuating mixture fractions and velocities within self-preserving round buoyant turbulent plumes. The following discussion of the study is brief, additional details can be found elsewhere [1-5].

Present considerations of self-preserving round buoyant turbulent plumes are confined to the buoyant jet sources used in most past studies of this flow, see Refs. 1-20 and references cited therein. Then, in the self-preserving region far from the source, all scalar properties are simple linear functions of the mixture fraction (which corresponds to the mass fraction of source material in a sample) called state relationships. Thus, the state relationship for density in the self-preserving region is as follows [1-4]:

$$\rho = \rho_\infty + f\rho_\infty(1 - \rho_\infty/\rho_o),\ f << 1 \tag{1}$$

Then, noting that the buoyancy flux of self-preserving round buoyant turbulent plumes is conserved, mean properties can be scaled as follows [1-4,19,20]:

$$\bar{u}((x-x_o)/B_o)^{1/3} = U(\eta) \tag{2}$$

$$\bar{f}\, g\, B_o^{-2/3}(x-x_o)^{5/3}\, |d(\ln\rho)/df|_{f\to 0} = F(\eta) \tag{3}$$

where from Eq. 1, $|d(\ln \rho)/df|_{f \to 0} = |\rho_o - \rho_\infty|/\rho_o$ while the universal functions $U(\eta)$ and $F(\eta)$ generally are approximated by Gaussian fits [1-6,12,13,15,16]. Thus, conditions required to reach self-preserving behavior, and the character of $U(\eta)$, $F(\eta)$ and other mean and turbulent properties within the self-preserving region, become central issues for these buoyant turbulent flows.

Numerous studies of self-preserving round buoyant turbulent plumes have been reported [6-20]. Unfortunately, there are considerable differences among the various measurements, which have been attributed to problems of reaching self-preserving conditions [1-3]. In particular, although past measurements generally satisfy Morton's [18] criterion for flows dominated by buoyancy, self-preserving behavior was generally claimed for $(x-x_o)/d$ in the range 6-62. This range of streamwise distances is small compared to nonbuoyant jets where recent measurements only indicate self-preserving behavior for $(x-x_o)/d \geq 70$ [21]. Thus, the objectives of the present investigation were to study mean and fluctuating mixture fraction and velocity properties at greater distances from the source, up to $(x-x_o)/d = 151$, in order to gain a better understanding of the structure of self-preserving round buoyant turbulent plumes and the requirements for the onset of this flow regime.

Experimental Methods. The experiments involved source flows of carbon dioxide and sulfur hexafluoride in still air at normal temperature and pressure, which provided downward-flowing negatively-buoyant round turbulent plumes. The plumes were observed in a 3000 × 3000 × 3400 mm high plastic enclosure within a high-bay test area. The enclosure had a screen across the top for air inflow, to compensate for the removal of air entrained by the plume. The plume flow was removed by 300 mm diameter ducts mounted on the floor at the four corners of the enclosure. The exhaust flow was controlled by a bypass/damper system to match plume entrainment rates, although recent work shows that roughly doubling and halving exhaust rates did not have a significant effect on flow properties [5]. The plume sources consisted of plastic tubes (6.4 and 9.7 mm inside diameter for the SF_6 and CO_2 sources, respectively) that could be traversed vertically and horizontally to accommodate rigidly-mounted instrumentation.

Instrumentation involved combined laser-induced iodine fluorescence (LIF) for measurements of mixture fractions and frequency-shifted laser velocimetry (LV) for measurements of velocities, as described in Ref. 22. The source flows were seeded with iodine vapor for the LIF measurements; the ambient air was seeded with oil drops (roughly 1 μm nominal diameter) for the LV measurements, using several multiple jet seeders that discharged near the top of the enclosure (maximum mixture fractions in the self-preserving region were less than 6%; therefore, effects of concentration bias of velocity measurements, because only the ambient air was seeded, were negligible).

Results and Discussion. Figures 1 and 2 are plots of the evolution of radial profiles of mean and fluctuating mixture fractions with streamwise distance. The variables used in these and subsequent figures are scaled according to the requirements of self-preserving round buoyant turbulent plumes. The results show progressive narrowing of the flow and increasing values near the axis with increasing distance until self-preserving behavior is reached for $(x-x_o)/d \geq 87$. This region is more than 12 Morton length scales from the source so that effects of buoyancy are dominant [18,19], with plume Reynolds numbers of 2500-4200 which are reasonably high for unconfined flows [1-4]. In agreement with the measurements of Papantoniou and List [20], which were made at similar distances from the source, the present self preserving plumes are narrower, with larger scaled values at the axis, than other past results [6-19] which appear to be in the transitional portion of the flow.

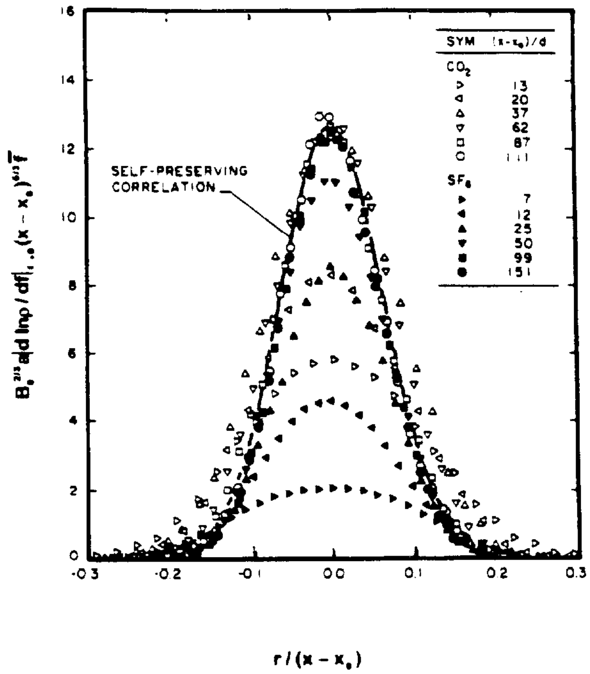

Figure 1. Development of radial profiles of mean mixture fractions. From [1].

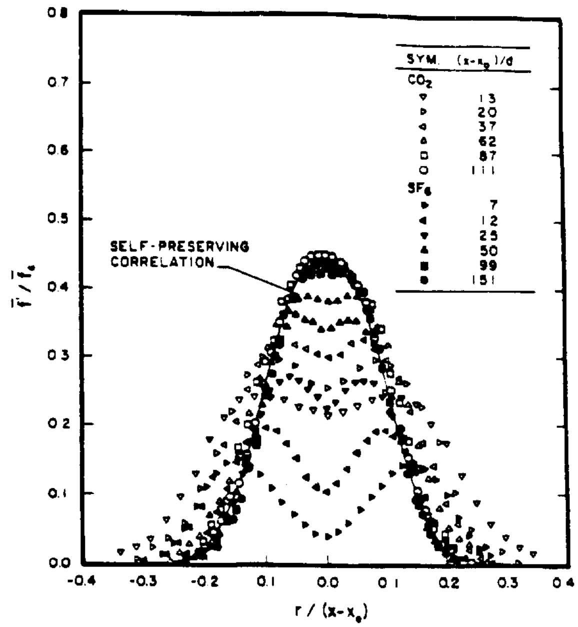

Figure 2. Development of radial profiles of rms mixture fraction fluctuations. From [1].

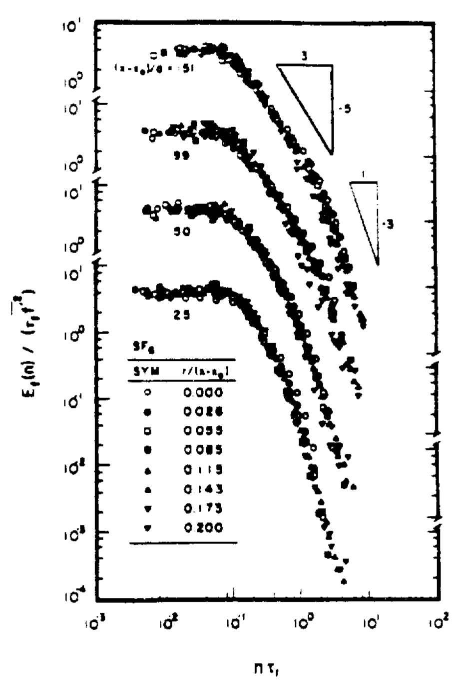

Figure 3. Temporal power spectral densities of mixture fraction fluctuations. From [1].

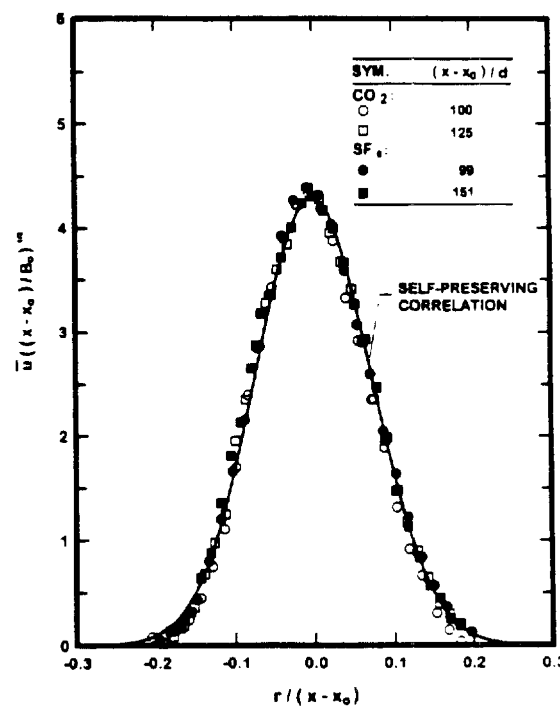

Figure 4. Radial profiles of mean streamwise velocities at self-preserving conditions. From [2].

Effects of buoyancy on the properties of turbulent plumes can be seen from the plots of mixture fraction fluctuations in Fig. 2. In particular, profiles of $\bar{f}'$ near the source exhibit a dip near the axis, similar to nonbuoyant jets [21], however, the dip disappears in the self preserving region yielding values of $\bar{f}'_c$ roughly twice those observed in nonbuoyant jets. This behavior can be attributed to turbulence production near the axis of the plumes due to buoyant instability in the streamwise direction [1-4].

Temporal power spectra of mixture fraction fluctuations, illustrated in Fig. 3, exhibit another interesting effect of buoyancy/turbulence interactions in buoyant plumes. In particular, the conventional -5/3 power decay of the temporal power spectra that is associated with the inertial subrange of turbulence, is followed by a prominent -3 power subrange that is not seen in nonbuoyant turbulence. This latter region is called the inertial-diffusive subrange where the local dissipation of turbulence kinetic energy is caused by buoyancy-generated inertial forces rather than viscous forces [15].

Figures 4 and 5 are illustrations of mean streamwise velocities and the three components of velocity fluctuations, respectively. The variables in these figures are scaled according to the requirements of self-preserving round buoyant turbulent plumes [1-4]. These measurements are all confined to $(x-x_o)/d \geq 87$, and properly exhibit self-preserving behavior. Similar to the findings for mixture fractions, the present measurements yield narrower profiles with larger scaled values near the axis than earlier results in the literature [6-19].

Effects of buoyancy are less evident for velocity fluctuations, Fig. 5, than for mixture fraction fluctuations, Fig. 2; in fact, velocity fluctuations exhibit a dip near the axis similar to the behavior of nonbuoyant jets, while turbulence intensities of streamwise velocity fluctuations near the axis are only slightly lower for self-preserving plumes, 0.22, than for nonbuoyant jets, 0.25, see [21]. Thus, buoyancy/turbulence interactions simultaneously act to increase mixture fraction fluctuation intensities and to reduce velocity fluctuation intensities near the axis of self preserving round buoyant turbulent plumes in comparison to round nonbuoyant turbulent jets. Another effect of buoyancy/turbulence interactions is that a prominent inertial-diffusive subrange with a -3 power decay with increasing frequency, is seen in the temporal power spectra of streamwise velocity fluctuations in self-preserving round buoyant turbulent plumes but is not seen in nonbuoyant turbulent plumes — analogous to behavior discussed earlier for mixture fraction fluctuations [2]. Other properties of velocity fluctuations in the self preserving region of buoyant turbulent plumes are qualitatively similar to nonbuoyant turbulent jets [19,21]; for example, $\bar{u}' > \bar{v}' \approx \bar{w}'$ near the axis while isotopic behavior is approached near the edge of the flow.

Present measurements of the three turbulence mass fluxes are illustrated in Fig. 6. The tangential turbulence mass flux is properly zero for the present axisymmetric flow. The streamwise turbulence mass flux is unusually large, exhibiting a correlation coefficient of roughly 0.7 near the axis, contributing roughly 15% to the total buoyancy flux of the plume, and helping to account for the enhanced production of mixture fraction fluctuations near the axis [3]. This behavior is caused by the intrinsic instability of plumes, where large values of f provide a corresponding potential to generate large values of u through effects of buoyancy [9]. Finally, the radial turbulence mass flux is reasonably consistent with other measured properties, based on evaluation using the governing equation for conservation of mean mixture fractions.

Present measurements of Reynolds stress for the self-preserving region of the plumes are illustrated in Fig. 7. The consistency of these measurements was checked using the mean

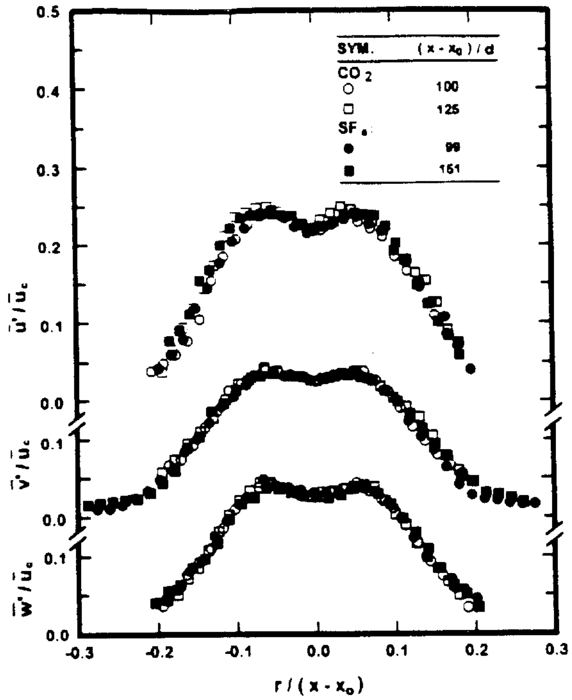

Figure 5. Radial profiles of rms velocity fluctuations at self-preserving conditions. From [2].

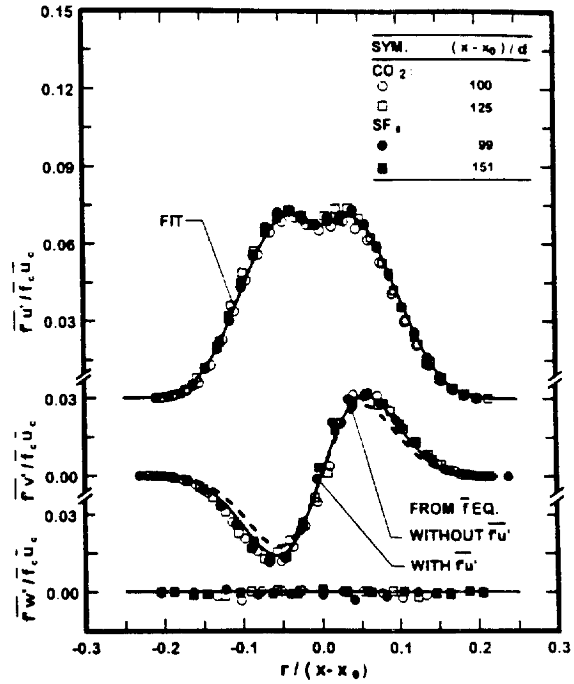

Figure 6. Radial profiles of turbulence mass fluxes at self-preserving conditions. From [3].

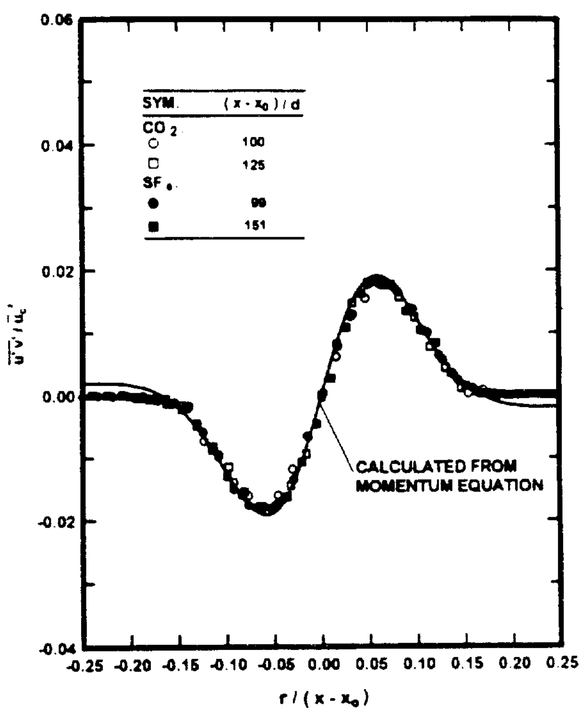

Figure 7. Radial profiles of Reynolds stress at self-preserving conditions. From [2].

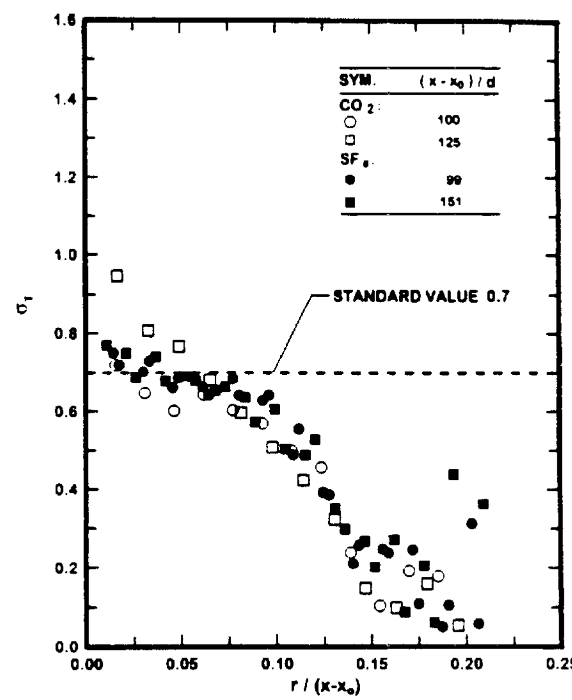

Figure 8. Radial profiles of turbulent Prandtl/ Schmidt numbers at self-preserving conditions. From [3].

momentum equation, analogous to earlier considerations of turbulent mass fluxes. These results are in reasonably good agreement in view of experimental uncertainties [2]. In general agreement with other velocity moments, the present results for plumes are rather similar to findings for nonbuoyant turbulent jets [21] in spite of the significant effects of buoyancy/turbulence interactions seen in mixture fraction properties.

Modeling Implications. Present measurements of the properties of self-preserving round buoyant turbulent plumes provide a direct means of evaluating both the performance and approximations of simplified turbulence models. In particular, Pivovarov et al. [23] tested a variety of contemporary turbulence models based on predictions of mean properties assuming self-preserving flow in round buoyant turbulent plumes and compared their predictions with the measurements of Refs. 9, 10, 12, 13 and 16 — all of which involve transitional plumes in view of present findings. Based on these results, Pivovarov et al. [23] recommended substantial changes of turbulence model constants established during extensive past studies of nonbuoyant turbulent flows. In contrast, these same predictions are in excellent agreement with present measurements of mean mixture fractions and streamwise velocities in self-preserving round buoyant turbulent plumes [4]. This apparent success, however, is somewhat misleading because predictions based on even simpler models — e.g., mixing length models — are generally effective for simple free turbulent boundary-layer flows at large Reynolds numbers such as round buoyant turbulent plumes. In fact, upon closer examination, present results highlight a number of serious difficulties of contemporary turbulence models of buoyant turbulent flows that will be discussed next.

A worrisome deficiency of simplified turbulence models involves their use of the gradient-diffusion approximation. Typical of simple turbulent boundary-layer flows, there is no immediate difficulty with the gradient-diffusion approximation in the radial direction for the critical radial turbulence mass fluxes and Reynolds stresses, illustrated in Figs. 6 and 7. On the other hand, the present flows yield unphysical effects of countergradient diffusion for streamwise turbulence mass fluxes in Fig. 6 for $r/(x-x_o) \geq 0.082$ and for streamwise turbulence stresses in Fig. 5 for $r/(x-x_o) \geq 0.042$ [3]. Naturally, these countergradient diffusion effects in the streamwise direction are not very important for boundary-layer flows, such as the present plumes, where streamwise turbulent transport is ignored in any event; nevertheless, these deficiencies raise concerns about the use of gradient-diffusion hypotheses for the more complex buoyant turbulent flows of practical interest.

Use of the simple gradient-diffusion hypothesis, with constant turbulent Prandtl/Schmidt numbers, is even problematical for transport in the radial direction within self-preserving buoyant turbulent plumes [3]. Direct measurements of this property for self-preserving round buoyant turbulent plumes are illustrated in Fig. 8. In view of experimental uncertainties, which are relatively large because σ_T involves several measurements including two gradients, σ_T exhibits self-preserving behavior reasonably well. Nevertheless, σ_T varies from a value near 0.8 at r=0 to a value near 0.1 at the edge of the flow, which departs significantly from assumptions of $\sigma_T = 0.7$ or 0.9 across the flow width that are made in simple turbulence models, see Refs. 4, 23, 24 and references cited therein.

Analogous to σ_T, other turbulence modeling constants also exhibit excessive variations across the flow width [3]. One parameter of interest is the ratio of the characteristic velocity to mixture fraction time scales, often denoted C_{g2} [24]. Near the axis C_{g2} is in the range 1.96-2.56, which is comparable to C_{g2} = 1.87-1.92 that is often used in simple turbulence models [24]. However, C_{g2} progressively increases with radial distance rather than remaining constant as assumed in the simple models, reaching values of 4.17-4.55 near the edge of the flow. Another parameter having similar importance is the constant, C_μ, in the gradient-diffusion approximation for the Reynolds stress. In particular, present values of C_μ near the axis are in the range 0.10-0.11, which is comparable to the widely used value, $C_\mu = 0.09$ of simple turbulence models [24]. Nevertheless, present measurements indicate a progressive reduction of C_μ with increasing radial distance, reaching values of 0.031-0.040 near the edge of the flow. Taken together, these difficulties also raise questions about the potential effectiveness of simple turbulence models for treating complex practical buoyant turbulent flows. This observation prompted measurements of a variety of properties used in higher-order closures, see Ref. 3 for a discussion of these results.

Conclusions. Measurements of mixture fraction and velocity statistics in round buoyant turbulent plumes in still and unstratified air has yielded the following major conclusions [1-5]:

1. Present measurements, supported by the earlier findings of Papantoniou and List [21] for similar conditions, indicated that self-preserving round buoyant turbulent plumes were narrower with larger mean values near the axis than previous results in the literature; the reason for these differences is that earlier measurements were limited to $(x-x_o)/d \leq 62$ which was not sufficiently far from the source to reach self-preserving behavior

2. Buoyancy/turbulence interactions in self-preserving round buoyant turbulent plumes are manifested in several ways: radial profiles of mixture fraction fluctuations do not exhibit reduced values near the axis that are seen in nonbuoyant jets; streamwise turbulent mass fluxes are large near the axis, they yield correlation coefficients of roughly 0.7 and they contribute roughly 15% to the plume buoyancy flux due to buoyant instability in the streamwise direction; and the temporal spectra of mixture fraction and streamwise velocity fluctuations exhibit prominent -3 power inertial-diffusive subranges, beyond the inertial subranges, that are not seen in nonbuoyant turbulent flows.

3. Evaluation of simplified turbulence models using the present measurements of mean properties in self-preserving round buoyant turbulent plumes was reasonably satisfactory but this is not definitive because plumes are a simple boundary-layer flow. In addition, several hypotheses concerning turbulence properties made for simple turbulence models were not satisfied very well; for example, streamwise turbulent transport exhibited countergradient diffusion, and several turbulence modeling constants (σ_T, C_{g2} and C_μ) exhibited significant variation over the flow cross section. Taken together, these difficulties suggest that higher-order turbulence models, or more advanced methods, will be needed to reliably treat the complex buoyant turbulent flows encountered in practical fire environments.

Nomenclature. B_o = source buoyancy flux, C_{g2} and C_μ = turbulence modeling constants, d = source diameter, $E_f(n)$ = temporal power spectral density of f, f = mixture fraction, $F(\eta)$ = scaled radial distribution function of $\bar{f}$, g = acceleration of gravity, n = frequency, r = radial distance, u = streamwise velocity, $U(\eta)$ = scaled radial distribution of $\bar{u}$, v = radial velocity, w = tangential velocity, x = streamwise distance, η = dimensionless radial distance = $r/(x-x_o)$, ρ = density, σ_T = effective turbulence Prandtl/Schmidt number, τ_f = temporal integral scale of mixture fraction fluctuations. The subscripts c, o and ∞ refer to conditions at the centerline, the source or virtual origin, and the ambient environment. The symbols $\bar{(\ )}$ and $(\ )'$ denote time-averaged mean and rms fluctuating values.

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Discussion

Craig Beyler: Your observation that you have to go very far downstream to get self-preserving flies in the face of the classical sort of thing where these self-preserving things work from the flame tip on in "real fires." I wonder what you think that means or what the relationship is between your experiments and those kinds of classic observations.

Gerard Faeth: I think probably the short answer to your question is that fires themselves are extremely complicated phenomena where the standards of what constitutes similarity are generally somewhat relaxed from the kinds of standards that we are trying to apply here. You simply aren't looking that closely and you have many other complicating features that are somewhat involved in the process. That's what I can say. One other brief thing here. For example, if you are willing to relax your standards, say you want to talk about something within 20 to 30%, now you are beginning to talk about distances that are only 25 diameters away.

Howard Baum: Did you record the amount of computational work required to do one of the Reynold's stress computations to simulate this as opposed to the κ-ϵ. I'm trying to get a feeling of the ratio of what the work actually is.

Gerard Faeth: The calculations for our conditions in both instances are sort of trivial and I haven't really tracked the answer to your question. I'll get the information.